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Estimation of wind misalignment and vertical shear from blade loads

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ABSTRACT

This paper describes the formulation and verification of a novel observer of wind parameters. The general idea behind the proposed approach is to consider the wind turbine rotor as an anemometer. In fact, the rotor responds to varying wind conditions; by properly interpreting this response, one can indirectly measure some desired wind characteristics, as for example yaw and shear, as described here.

Measurements of wind conditions obtained this way are not affected by the usual disturbances of existing sensors, for example when installed in the nacelle or in the rotor wake. Furthermore, the approach provides rotor-equivalent quantities, and not the typical point information provided by wind vanes, anemometers or other similar sensors, whose information might be too local for large rotors.

The proposed method is here formulated for the observation of wind direction and vertical shear. The new observer is demonstrated first in a comprehensive simulation study using high-fidelity aero-servoelastic models, and then experimentally using an aeroelastically-scaled wind tunnel model.

1. Introduction and motivation

In addition to wind speed, the knowledge of wind parameters such as direction and shears can be useful for control purposes. In fact, wind direction information drives yaw control that reduces the misalignment between wind and rotor. On board wind turbines, yaw control is needed because operation at high yaw angles causes a number of undesirable effects. For instance, the power available in the wind incident over the rotor is reduced with the third power of the cosine of the yaw angle; to give an example, operating at 20 deg of yaw reduces the available power of about 17%. Furthermore, yawed flow changes the angle of attack of the airfoils, which can further degrade aerodynamic performance besides the cosine effect mentioned above. In addition, wind-rotor misalignment generates side–side loads that tend to excite low damped modes of the machine, thereby inducing loads and vibrations, which in turn increase fatigue damage to the machine components.

Although it would appear beneficial to operate at low yaw because of the above reasons, these effects need to be carefully weighed against the cost of frequent yaw actuation. In fact, yawing the nacelle and rotor of a modern large wind turbine requires moving a very massive structure (for example weighing in excess of 150 tons for a typical 3.0 MW machine). This means overcoming the static friction in the yaw bearing when initiating the maneuver and slowing down the motion once the new alignment is reached, while limiting gyroscopic and aerodynamic loads throughout the whole maneuver. Hence, to reduce cost, complexity, size and maintenance of the yaw actuation system, its duty-cycle must be carefully limited.

In practice, such trade-offs between operation in yawed flow and yaw actuation are translated into control policies that realign the machine only when the yaw error exceeds a sufficiently large predetermined threshold for a sufficiently long period of time. The fact that yawing is important for performance and loads, but must be done only when really necessary because of the reasons noted above, implies that one would like to have precise and reliable measurements of the yaw angle, so as to yaw only for the right reason, of the right amount and at the right time.

Unfortunately, high-quality measurements of yaw are difficult to obtain. In fact, on-board yaw sensors, typically wind vanes, are affected by various sources of inaccuracy, including disturbances caused by the rotor wake and its turbulence, the presence of the nacelle, the periodic passing of the blades upstream of the instrument, etc. Although most sensors can be calibrated for compensating these effects, it is well known that the resulting wind measures are typically not very reliable nor accurate. Furthermore, existing sensors, even when well compensated for all sources of error, can only provide *point* (i.e. extremely local) information, usually at hub-height. For the very large diameters of modern wind

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Notation

a	axial induction factor
c	blade chord
C_{l_α}	lift curve slope
e	blade equivalent hinge offset
g	gravitational acceleration
I_b	equivalent flap inertia
K	non-dimensional flapping frequency
K_1	vertical wind shear gradient
K_β	equivalent flap stiffness
l	yaw moment arm, i.e. distance between yaw axis and rotor center
m	blade bending moment
M_b	blade mass
N	number of revolutions for signal demodulation
$N_\mathcal{I}$	number of observations in identification data set $\mathcal{I}$
$N_\mathcal{V}$	number of observations in verification data set $\mathcal{V}$
q	yaw rate
R	rotor radius
t	time
U_0	cross-flow
V_0	free-stream wind speed
x_g	non-dimensional span-wise center of gravity location
$\boldsymbol{M}$	matrix of measured driving inputs
$\boldsymbol{T}$	matrix of unknown model coefficients
$\boldsymbol{W}$	matrix of measured wind parameters
$\mathcal{I}$	identification data set
$\mathcal{V}$	verification data set
β	blade flap angle
β_0	coning angle
γ	Lock number
λ	non-dimensional inflow
Ω	rotor angular speed
ψ	azimuth angle
ρ	air density
θ_p	blade pitch
φ	misalignment angle, $\varphi = \mathrm{a}\tan(U_0, V_0)$
$(\cdot)^T$	transpose
$(\cdot)^{IP}$	rotor in-plane component
$(\cdot)^{OP}$	rotor out-of-plane component
$(\cdot)_b$	quantity pertaining to blade b
$(\cdot)_k$	quantity pertaining to the kth trim point
$(\cdot)_{1c}$	first cosine harmonic
$(\cdot)_{1s}$	first sine harmonic
$\overline{(\cdot)}$	non-dimensional quantity
$(\cdot)'$	derivative wrt azimuthal angle, $\mathrm{d}/\mathrm{d}\psi$
$(\cdot)''$	second derivative wrt azimuthal angle, $\mathrm{d}^2/\mathrm{d}\Psi^2$
BEM	blade element momentum
FBG	fiber Bragg grating
HAWT	horizontal axis wind turbine
LiDAR	light detection and ranging
LQR	linear quadratic regulator
MBC	multi-blade coordinate
MW	mega watt

turbines this limitation can provide for an additional source of error, and a more global view of the wind direction over the rotor disk would be more appropriate.

Although the use of wind shear information is not as straightforward nor commonly used as wind direction, it is reasonable to assume that good quality wind shear information could be profitably exploited. For example, wind shear could be used to enhance the performance of wind turbines by the scheduling of control gains, or to lower the loads induced by such non uniform inflow conditions, for example by providing a feed-forward input that might be used for individual blade pitch control. Additional applications are foreseeable in wind farm control by the gathering of shear information throughout a wind farm without the need for additional sensors, by simply using the wind turbines as anemometers.

Goal of the present work is the development and testing of a yaw and vertical shear observer that overcomes the limitations of currently available point-wise sensors. To our knowledge this problem has not yet been successfully solved before. The approach proposed herein uses the whole rotor, and more specifically the blade loads, to infer these wind states. This way all limitations of current sensors are removed, including the one regarding the localized information that they provide.

The idea of designing observers to support the operation of wind turbine control systems and overcoming the inherent limitations of anemometers has been explored in the past, although limitedly to the observation of the wind speed, as for example in Refs. [15–17]. The problem is typically solved by using the dynamic torque balance equation of the rotor; by measuring the rotor speed and blade pitch, one can infer from that single equation, typically using a Kalman filter, an estimate of the wind effective (i.e., averaged throughout the rotor response) speed.

Generalized wind observers that can estimate various wind states, including wind speed, vertical and horizontal shear and yaw, have been described in Refs. [4,5,18]. The generalized approach uses a larger number of dynamic equilibrium equations, by adding to the torque balance also the fore-aft, side–side and blade flap dynamic equilibrium. This expanded set of equations allows one to reconstruct, again with a Kalman filter, a richer picture of the spatial distribution of the wind over the rotor disk. However the formulation is complicated and occasionally not fully robust, due to the fact that multiple wind states have in general a low level of observability. In fact, using that approach, it is at times hard to discriminate from one another the effects of the various wind states from the response of the machine.

Here we develop a different and simpler approach that exhibits improved accuracy and robustness with respect to the one of Refs. [4,5,18], and overcomes the low observability problem. The new method is based on the first order harmonic blade response. In fact, by using a simplified model of a flapping blade, it is shown here that blade harmonics have a specific dependence on the wind characteristics and that each wind state, for example shear or yaw, leave a specific recognizable mark on the harmonic response of the blades. By using this fact, one can reliably infer at all times those wind states, simply by looking at the first harmonics of blade loads. These quantities can be readily obtained by processing on-line measurements obtained by suitable sensors, such as strain gages or optical fibers.

The paper starts off by showing the observability of yaw and shear by inverting the 1P response of an analytical blade flapping model. This derivation provides the structure that an observation model of these wind parameters could have, but it is not applicable in practice for the intrinsic limitations and simplifications underlying the analytical model. To overcome this problem, a more general observation model is then proposed, that maintains the same structure of the analytically derived one, but whose parameters are obtained by system identification, here based on a least-squares approach.